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USE OF MODELS TO STUDY FOREST FIRE BEHAVIOR

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ABSTRACT

The U. S. Forest Service has started a laboratory study with the ultimate objective of determining model laws for fire behavior. The study includes an examination of the effect of such variables as species of wood, density of wood, moisture content, size of fuel particle, spacing, dimensions of fuel bed, wind, and slope on the rate of spread of fire and the partition of energy.

Fuel beds in the form of cribs made of square cross-section wood sticks were chosen for diagnostic studies. The crib is ignited at one end and moved in such a manner that the flame is kept in a fixed position in space. The rate of spread of the fire is determined by the rate at which the crib is moved. After an initial period of growth, the fire reaches a steady-state, which permits measurements to be made of certain dependent variables over an extended period.

A series of tests were made using five species of wood with varying densities to determine the effect of density on rate of spread. The species were white fir, magnolia, basswood, sugar maple, and longleaf pine. Results show rate of spread decreases with increasing density, and for a given wood density it is practically independent of the species tested. Another series of tests were made using white fir wood at several densities to determine the effect of fuel moisture content on rate of spread. The results show that the effect of moisture content on rate of spread is greater with decreasing density of wood.

The temperature distribution measured in the convection zone of test fires was expressed as a functional relationship between two dimensionless groups, one pertaining to atmospheric conditions and convected heat and the other to the height and diameter of the convection column.

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INTRODUCTION

A. General

Until a quantitative prediction of the persistence and spread of a fire under given conditions is possible, we cannot pretend to understand the process of fire-front propagation in a sufficiently exact way to provide much assistance in directing our efforts to the control of forest fires. An expression for the rates of combustion as a function of fineness and arrangement of the fuel, fire geometry, fuel moisture content, and surrounding atmospheric conditions is needed to understand the basic principles of ignition, fire buildup, and spread. The possibility of similarity between various systems of even wholly unrelated fields suggests the exploration of the phenomena of fire behavior by means of "models" on a reduced scale.

The use of models in scientific research and for industrial purposes is well known. A few examples in scientific research are: wind tunnels used to study flight problems, models of riverbeds used to study erosion of soil, the use of water channels to study ship models, and the recent use of shock tubes to study the hypersonic-flight regime. Less well known is the use of models to study problems encountered in the design of combustion equipment, and much less well known is the use of models in the study of forest fire behavior. The use of models is more feasible and in the long run less costly than experiments on a full scale; this is particularly true in large-scale forest fires. To quote Dr. Baekeland, inventor of Bakelite, "Commit your blunders on a small scale and make your profits on a large scale."

B. Current Program

At the two new U. S. Forest Service forest fire research laboratories, facilities are now available to conduct model studies of forest fire behavior. From the several possible types of model, the initial one selected for study permits establishment of a steady-state condition for the free-burning of solid fuels. This model allows examination and measurement of those parameters which govern combustion over an extended period of time. The model represents on a reduced scale a section of the combustion zone of a moving fire front burning in a homogeneous fuel bed without spotting.

A systematic program has been planned around this initial steady-state model of a free-burning fire with the following objectives:

I. To study this type of system with experimental fire models in which fuel, fuel bed, fire base, and atmospheric conditions are controlled; to evaluate quantitatively the effects of each variable on the fire; and to ascertain the model laws for fire properties including rate of fire spread.

II. To obtain information about the effects of the properties of the air, fuel, and base on the following:

1. Total rate of energy release
2. Distribution of the released energy
3. Temperature, pressure, convection, and radiation pattern in and around the fire

III. To achieve a heat balance on a free-burning wood fire.

To date about 100 experimental fires have been burned using this steady-state model. Measurements for these fires were made on many of the dependent and independent parameters. The diagnostic usefulness of the model in studying fire behavior is illustrated by the results obtained, which show the effect of moisture content and density of wood on the rate of burning or spread. The functional usefulness of the model is shown by an analysis of data obtained on model test fires, which characterizes the temperature field of the convection column produced by a free-burning fire.

STEADY-STATE FIRE MODEL

The essential elements of the steady-state fire model are: a wood fuel bed built in the form of a crib, a combustion table equipped to transport the fuel bed at a controlled rate, a base of inert material of known density, and sensing and recording instruments to measure specified variables (1).[1/]

The fuel bed is a crib of wood sticks of square cross section (fig. 1). The physical features of such a crib can be controlled; for example, the species, density, and moisture content of the wood, the stick size, the spacing between sticks, and the width and height of the crib. The crib is formed by placing the sticks in tiers with a particular spacing between sticks. A drop of resorcinal-formaldehyde resin glue is placed on each junction to bond the crib into a rigid assembly. For several weeks before burning, the crib is conditioned to moisture equilibrium in an atmosphere of constant temperature and relative humidity.

The ignition device is a narrow, shallow trough containing an asbestos wick saturated with a hydrocarbon liquid fuel. To start the test, one end of the crib is set on fire by igniting the asbestos wick. The fire gradually spreads to the other end of the crib, reducing the wood to a residue of ash and charcoal.

The combustion table (fig. 1) is equipped with a chain-belt mechanism which moves the crib and two heavy asbestos sheets, one on each side of the fire, in synchronism with the flame spread to simulate the relative movement of the fire front in relation to the ground. The crib and its

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1/ Underlined numbers in parentheses refer to References at the end of paper.

inert base rest on the chain-belt, which is moved manually by a gear drive in order to hold the flaming zone of the burning crib in a fixed position.

Two important features of the model are: (1) The crib used is made relatively long and a zone or band of fire travels the length of the crib. After an initial buildup, the rate of burning or spread reaches a constant value, which holds until near the end; this overcomes the difficulty of investigating a fire that starts small, grows to a maximum, then declines. (2) The position of the flaming zone is held fixed in space by moving the fuel into the fire. This method permits a grid of thermocouples in the flame and convection column, radiometers surrounding the fire, and other sensing devices to be stationary. The rate of burning or spread is the rate the crib is moved to maintain the flame in a fixed position (fig. 2).

RESULTS AND DISCUSSION

A. Period of Steady-State Burning

The duration of the steady-state burning period is limited only by the buildup period and the length of the crib. The buildup period or time for the burning to reach a steady-state condition after one end of the crib is ignited is dependent upon such factors as density and moisture content of the wood and stick size. Typical curves for the spread of fire through cribs showing the buildup and steady-state periods for cribs of different wood density are presented in figure 3.

B. Influence of Species of Wood on Rate of Spread

The species tested were white fir, magnolia, basswood, and sugar maple, all being nonresinous woods; and longleaf pine, a resinous wood. The cribs for these tests were 5.5 inches high, 9.25 inches wide, and 35.5 inches long, made from nominal 1/2-inch square sticks with a spacing of 1.25 inches between sticks in each tier. Several fires were burned of each species over a range of densities and at a moisture content of approximately 10.5 percent. Results of these test fires are shown in figure 4. It is evident from figure 4 that basswood has a higher rate of spread than the other four species. This would indicate that some wood property other than density has an added effect on rate of burning of this wood. Basswood has an oil rich in volatile fatty acids (2), and this may account for the higher rate of burning. On the other hand, longleaf pine, a resinous wood, has practically the same rate of spread as white fir, maple, and magnolia. The results for longleaf pine indicate that the resin in wood does not increase the rate of burning; in fact, it appears to act as a deterrent.

C. Influence of Density and Moisture Content of Wood on Rate of Spread

Results of tests on the five species (fig. 4) indicate that white fir and sugar maple produce a nearly continuous curve for rate of spread as a function of density. White fir and sugar maple were therefore selected for tests to determine the influence of moisture content of wood over a range of densities from 0.300 to 0.800. Cribs and stick sizes and stick spacings for these tests were identical to those used in determining the effect of species of wood on spread. Five series of tests were made to determine the effect of density on rate of spread for different levels of moisture content. Results of these tests are shown in figure 5.

Figure 5 provides several findings useful to the understanding of forest fire behavior. The two most important ones are: (1) the effect of moisture content of wood on rate of spread decreases as the density of wood increases; (2) the rate of spread of fire increases rapidly with decreasing moisture content for densities less than 0.45 and moisture contents less than 10 percent.

Litter, bark, moss, grass, leaves, and partially decomposed wood which have densities of less than 0.45 are the forest fuels which mainly contribute to the spread of most forest fires. The results show that moisture content of such fuels becomes extremely important in the behavior of forest fires, especially when their moisture content is less than 10 percent.

D. Temperature of Convection Column

Temperatures of the convection column from the model fires are taken with a grid of 33 No. 30 chromel-alumel thermocouples above the combustion table. The type of data thus obtained is illustrated by figure 6,which shows temperatures across the column at three different elevations above the burning crib. At a height of 47 inches the column from this model fire is narrow and the peak temperature is slightly higher than 800°F. At a height of 120 inches the column is much wider and the peak temperature is about 200°F. For this same fire, figure 7 shows the vertical distribution of temperature up the central axis. The temperature 1 inch above the crib, in the region rich in volatiles that are being distilled from the wood and lean in air, is lower than the temperature of the flame in the region 15 inches above the crib,where a maximum of 1650°F. is reached.

The natural convective movement of the heated column above fires is responsible for the air entrainment into the column. The behavior of fire brands or burning embers is affected by the velocity and temperature profiles of the convection column. To gain a fundamental understanding of the convection zone of a fire burning in a free atmosphere, Scesa and Sauer (3) and Yih (4) made theoretical analyses of the transport processes for point and line heat sources based on heat transfer and fluid flow theories.

The equation, giving temperature distribution within a turbulent column above a point source (3), was rearranged into a functional relationship between dimensionless height and dimensionless temperature rise as follows:

$$\frac{\Delta\theta \; g \; Z^{5/3}}{\theta_o (Q/C_p \; \theta_o \; \rho_o)^{2/3}} = \phi\left(\frac{y}{Z}\right)$$

In this equation, $\Delta\theta$ is the temperature rise above ambient θ_o, Q is the rate of convective heat generated by the fire, C_p and ρ_o are, respectively, the specific heat and density of the ambient air entering the column, g is the acceleration of gravity, Z is the vertical distance from the point source, y is the distance normal to the source axis, and ϕ indicates a functional relation.

The temperature data of the convection column from 20 fires in cribs 5.50 inches high and 9.25 inches wide were correlated using the above functional relationship between the dimensionless temperature rise and the ratio of radial distance to height or dimensionless height. Since the crib fires are finite sources, a distance of 1/2-foot was arbitrarily added to height distances to adjust values of Z to the vertical distance from a point source. Figure 8 shows graphically the relationship of the two dimensionless groups which characterize the temperature field of the convection columns resulting from these wood crib fires.

CONCLUSION

It is believed that studies with models, such as the steady-state model described herein, will contribute much basic knowledge needed for presuppression and suppression planning in forest fire control. The results presented illustrate that modelling of free-burning wood fires can be of great help to the understanding of fire behavior and can contribute much basic information on the variables which control the spread of forest fires. Such information should provide fire researchers with a means of exploring new and revolutionary techniques of controlling large-scale fires with minimum expenditures of time and resources.

ACKNOWLEDGMENT

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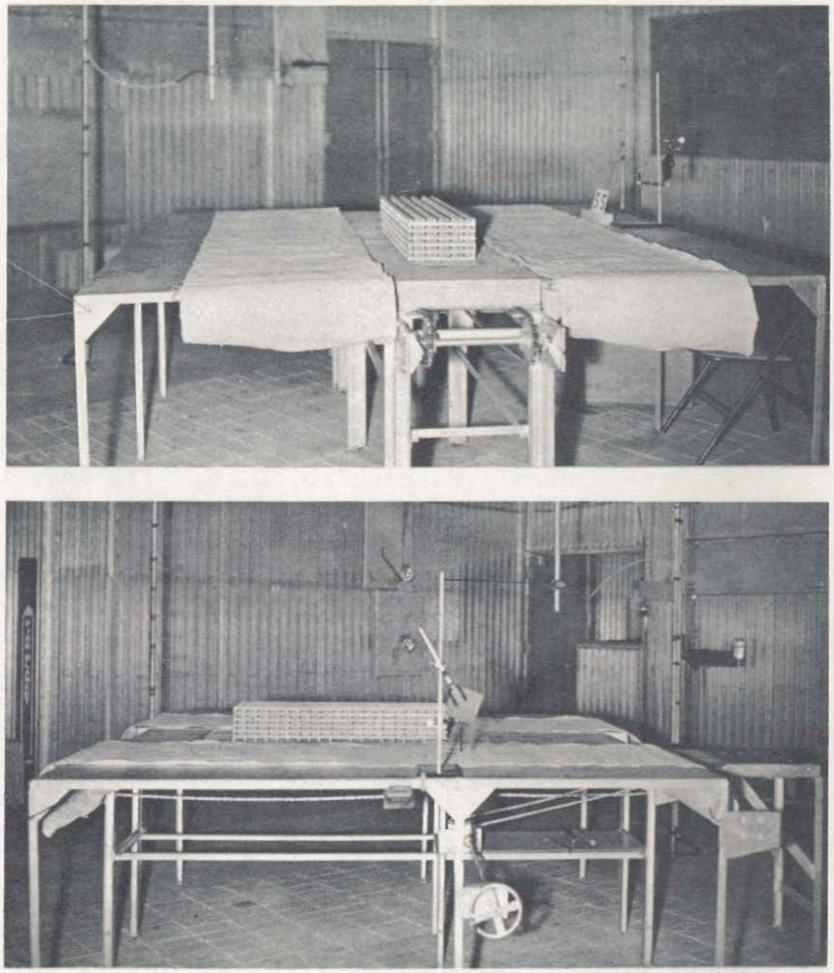

Figure 1.--End and side views of combustion table showing the chain-belt drive mechanism with concrete base slabs, asbestos sheets on either side, operator's hand wheel, and a wood crib in place for a test fire.

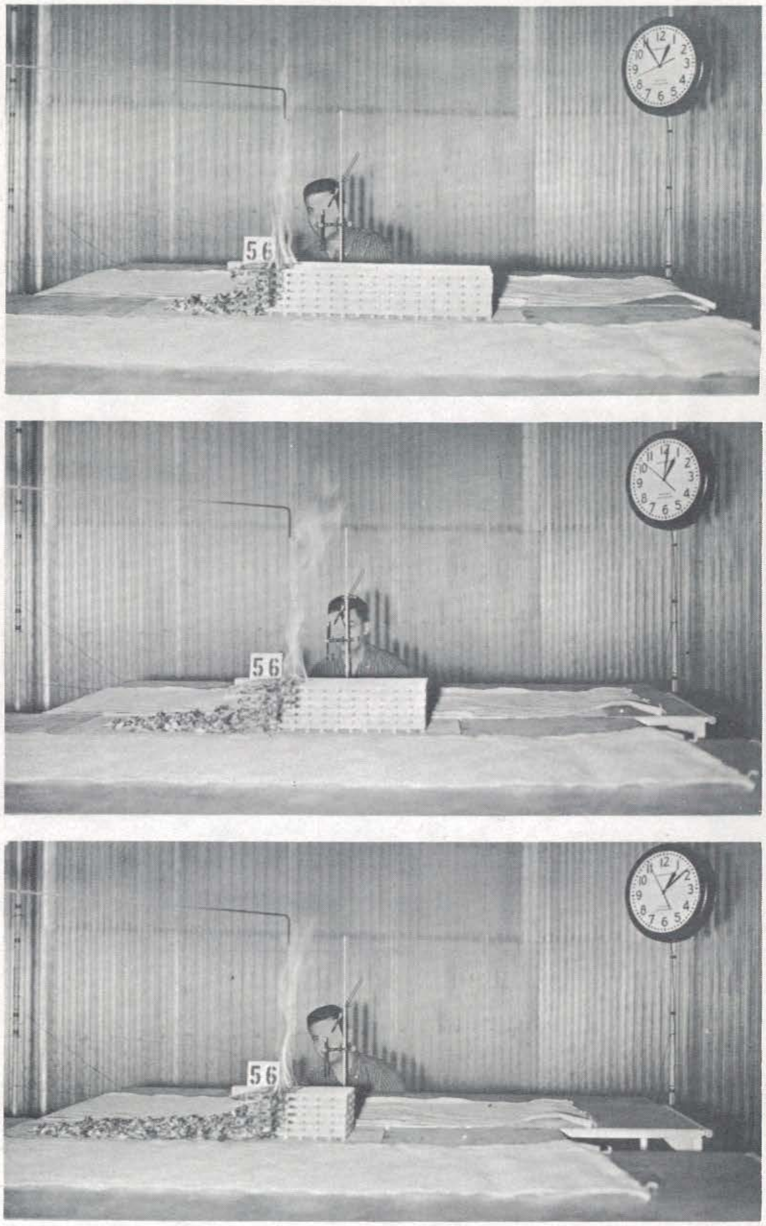

Figure 2.--Crib fire at different times during the test, illustrating the fixed position of the flame as the crib is moved.

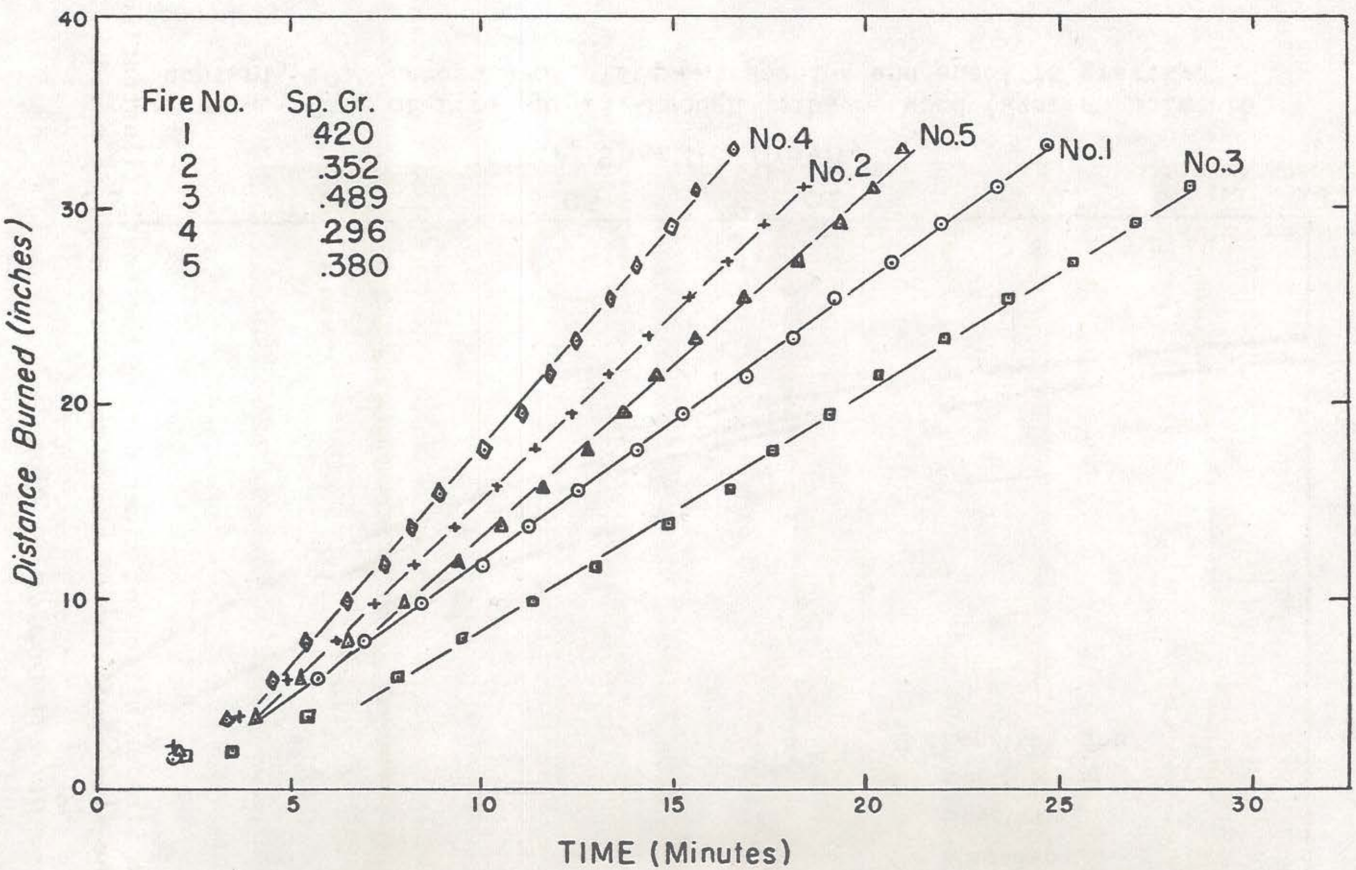

Figure 3 .--Rate of spread of fire through cribs of white fir wood (1/2-inch square; M.C., 10.5%; crib height, 5.5 inches; crib width, 9.25 inches; spacing 1.25 inches) varying in specific gravity.

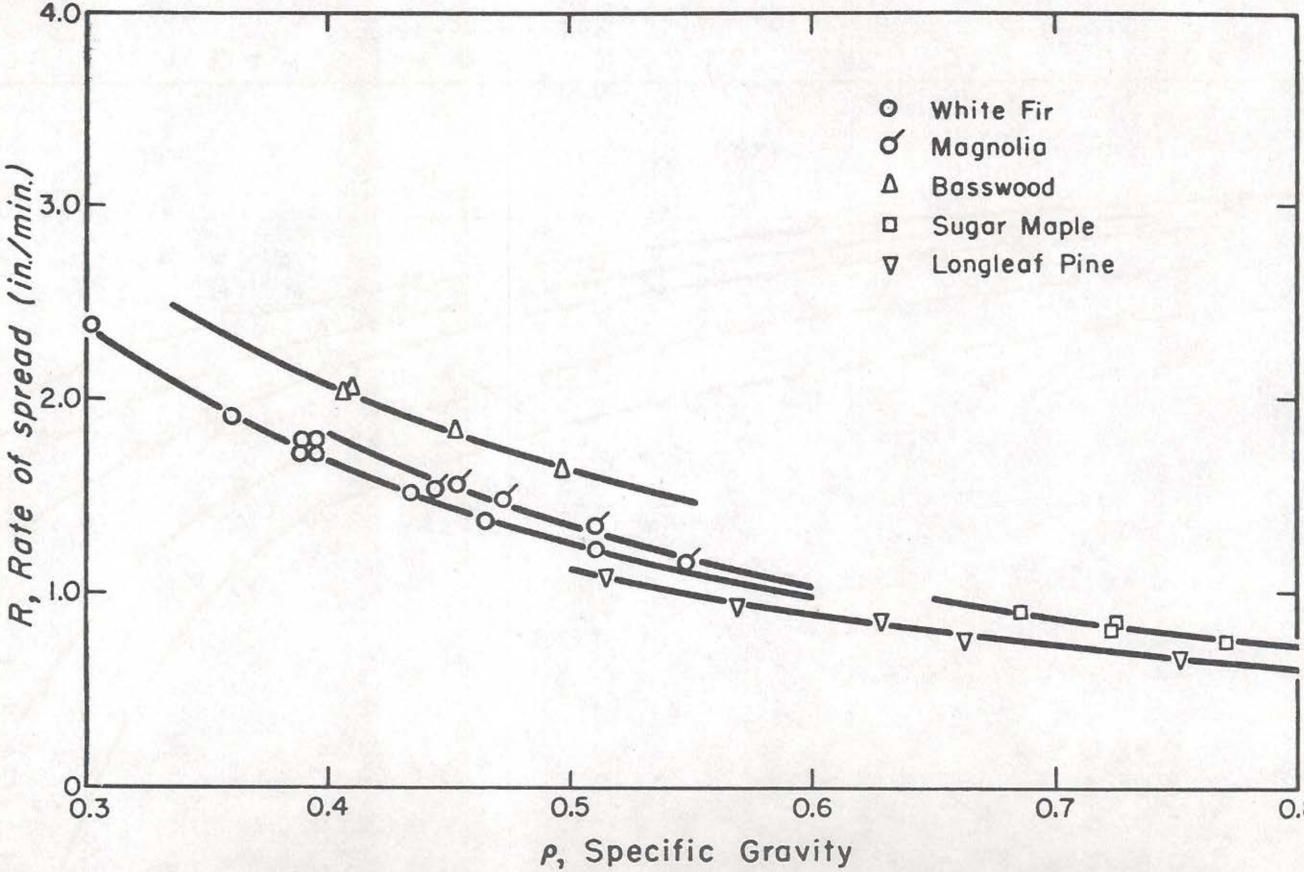

Figure 4.--Rate of fire spread through cribs of wood (average moisture content, 10.5 percent) of different species and specific gravity.

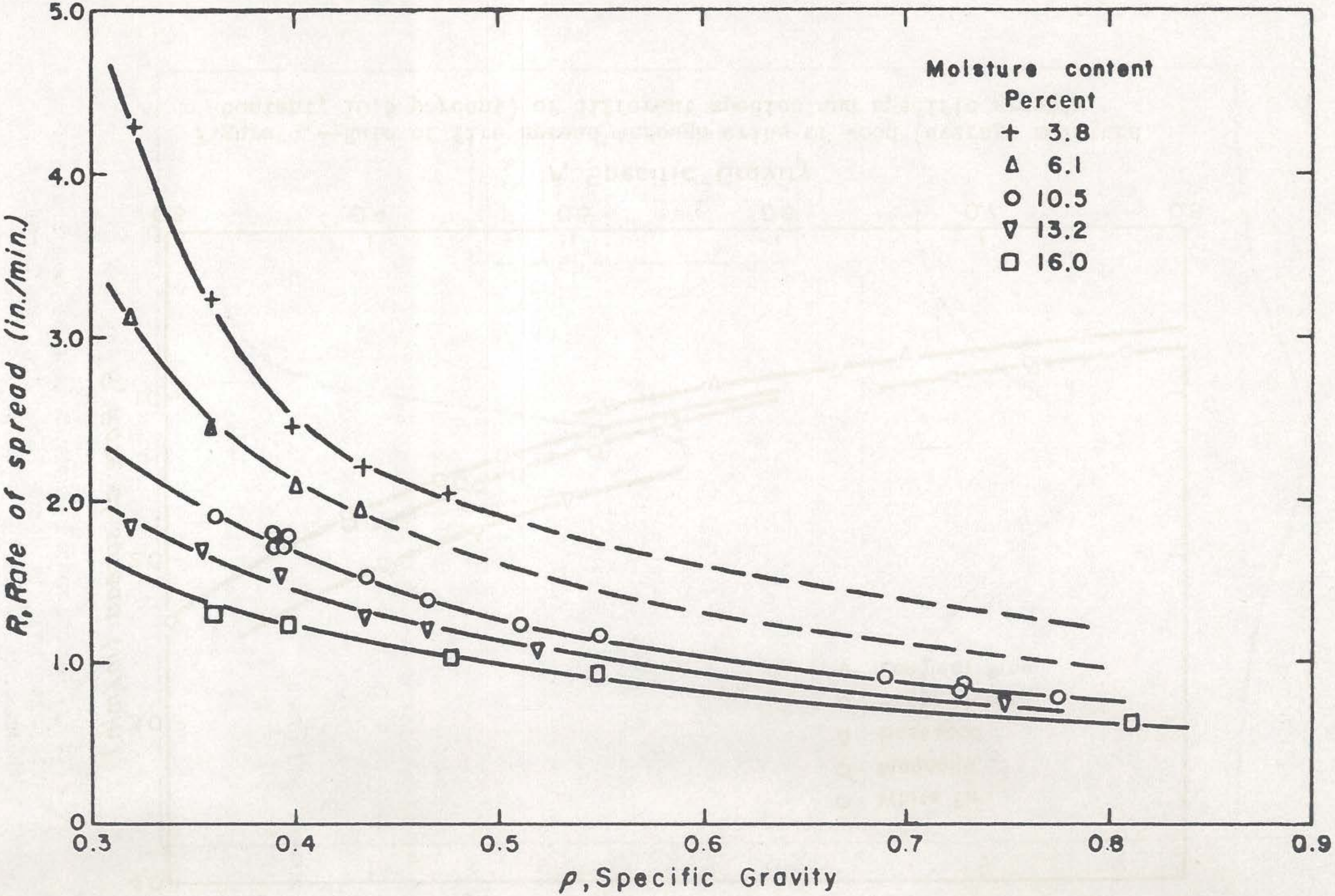

Figure 5.--Effect of density of wood on rate of fire spread through cribs at different moisture content.

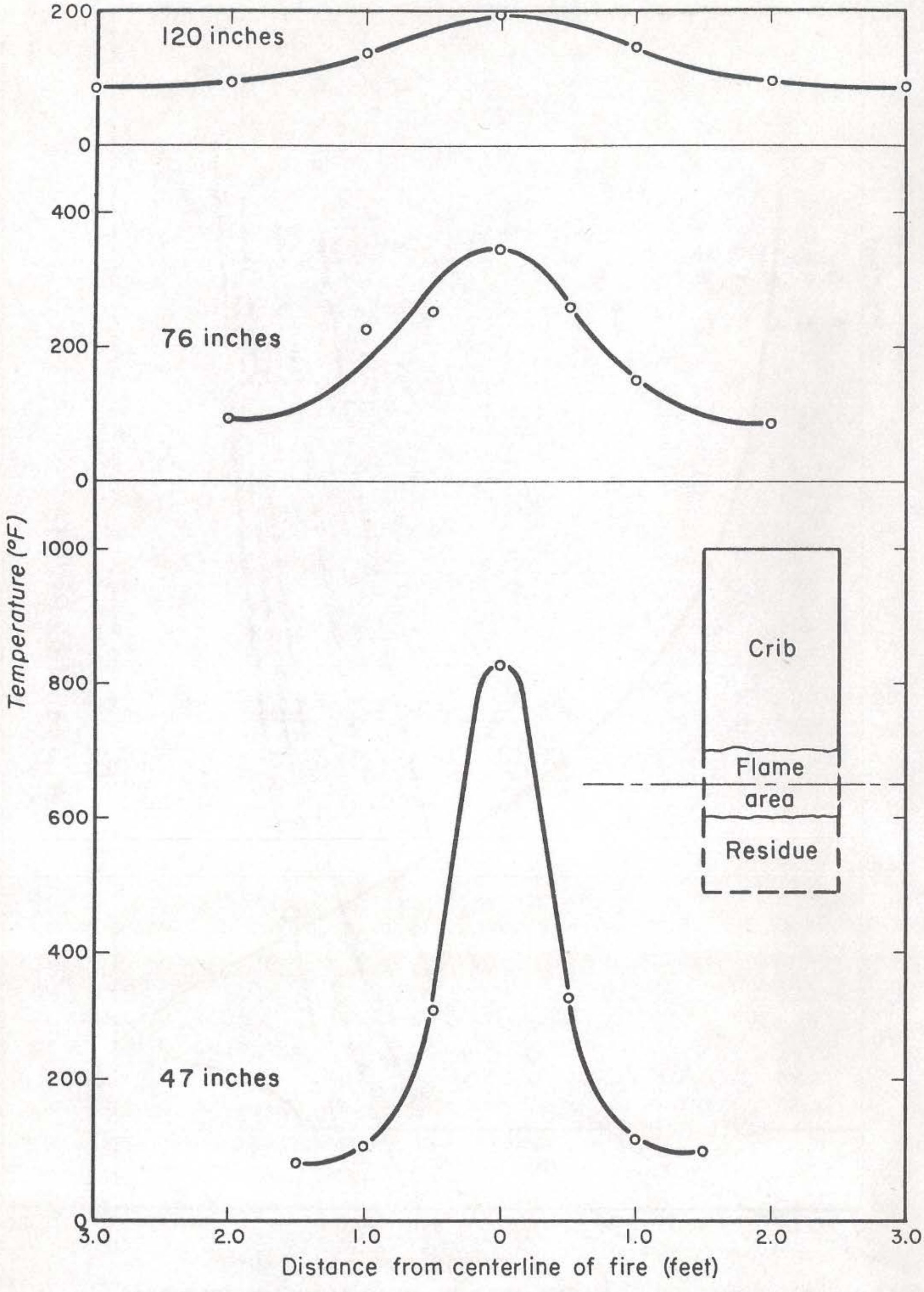

Figure 6.--Horizontal distribution of temperatures at three heights above table top, measured by thermocouples during Fire No. 16.

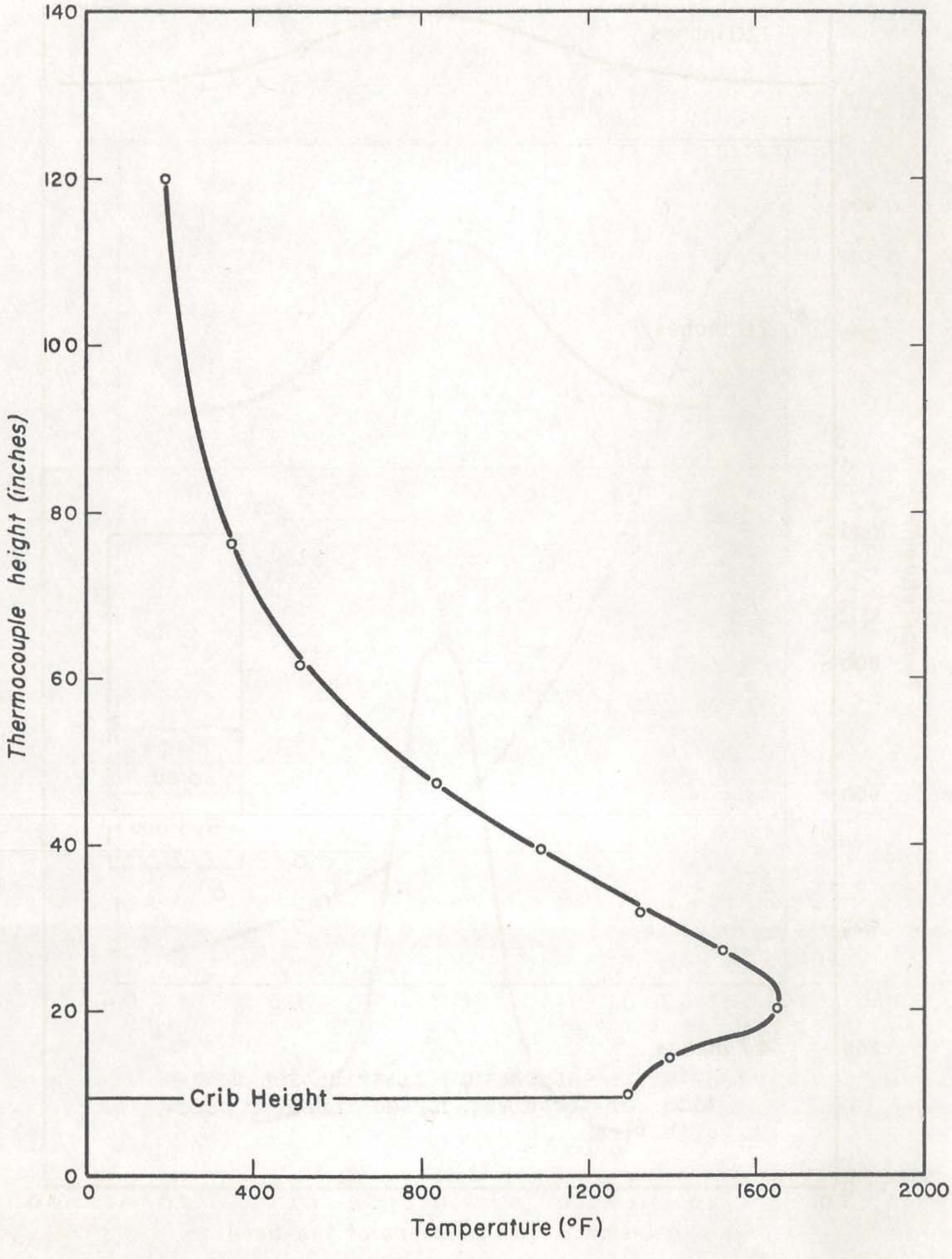

Figure 7.--Vertical temperature distribution along central axis of flame and convection column during Fire No. 16.

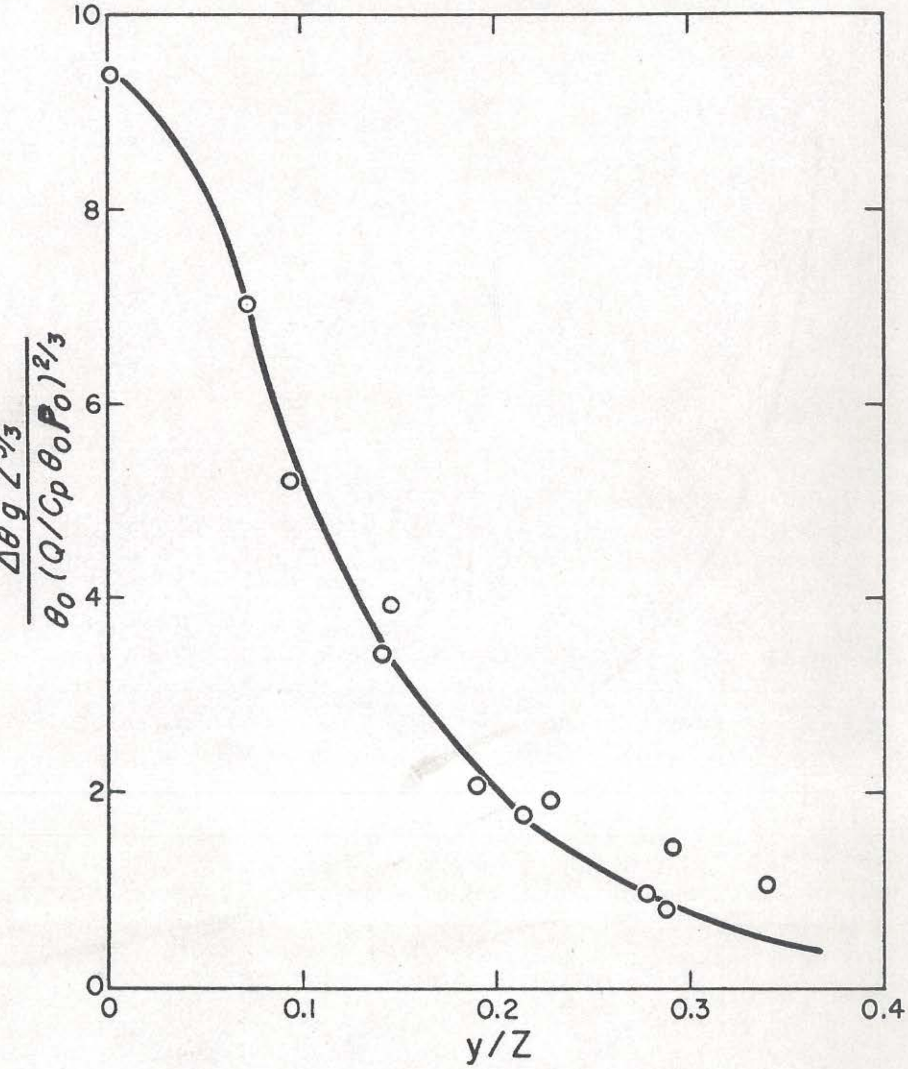

Figure 8.--Temperature distribution function for turbulent convection over wood-crib fires.